Precise predictions for Higgs-masses in the Next-to-Minimal Supersymmetric Standard Model (NMSSM)

Peter Drechsel

in collaboration with L. Galeta, S. Heinemeyer and G. Weiglein

Deutsches Elektronen-Synchrotron (DESY)

July 16, 2014

Outline of Project

Aim:

- precise prediction of Higgs-masses in the NMSSM for implementation into FeynHiggs [Heinemeyer, Weiglein, Rzehak, et. al. '10]

Means:

- diagrammatic methods, automated calculation using FeynArts-Modelfile (used for previous publications, e.g [Heinemeyer, Weiglein, Zeune, et. al. '12]), work in progress

NMSSM: Scalar Higgs-Sector

Mixing of the gauge to mass eigenstates

	Gauge-	Mass-
	Eigenbasis	
CP-even	$\phi_1,\ \phi_2,\ \phi_s$	$h_1,\ h_2,\ h_3,$
CP-odd	$\chi_1,\ \chi_2,\ \chi_s$	$G^0,\ a_1,\ a_2$
charged	$\phi_1^\pm,\ \phi_2^\pm$	$G^\pm,\ H^\pm$

Minimization of potential on classical level

$$H_1 = \begin{pmatrix} v_1 + \frac{1}{\sqrt{2}}\left(\phi_1 - \mathrm{i}\chi_1\right) \\ -\phi_1^- \end{pmatrix} \qquad H_2 = \begin{pmatrix} \phi_2^+ \\ v_2 + \frac{1}{\sqrt{2}}\left(\phi_2 + \mathrm{i}\chi_2\right) \end{pmatrix}$$

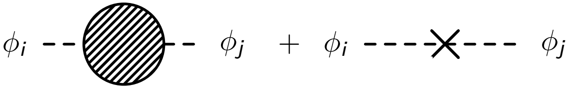
$$S = v_s + \frac{1}{\sqrt{2}}\left(\phi_s + \mathrm{i}\chi_s\right)$$

Calculation: Mass Definition

pole mass for a scalar field ϕ_i

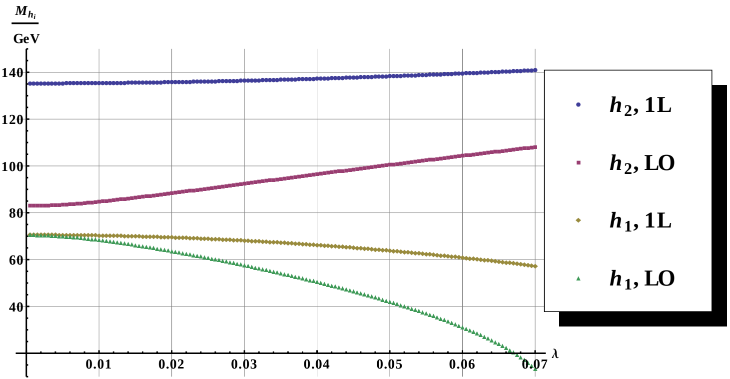
$$0 = \left[\mathrm{i}\left(p^2 - M^2_{i,\mathrm{tree}}\right) + \mathrm{i}\hat{\Sigma}_{ii}(p^2) \right]_{p^2 = \widetilde{M}^2_{\mathrm{pole}}}, \;\; M_i^2 = \mathrm{Re}\, \widetilde{M}^2_{\mathrm{pole}}$$

$$\mathrm{i}\hat{\Sigma}^{(1)}_{\phi_i\phi_j}(p^2) =$$



$$= \text{finite}$$

Results: Numerical Scenario I



Parameter

$$M_{H^\pm} = 250\ \text{GeV},\ X_t = X_b = 2\ \text{TeV},\ M_{\tilde{q}} = M_{\tilde{q}_R} = 1\ \text{TeV},\ A_\kappa = -100\ \text{GeV},$$
$$\mu_{\text{eff}} = 250\ \text{GeV},\ \kappa = \frac{\lambda}{5},\ \tan\beta = 5,\ \mu_{\text{ren}} = m_t = 173.3\ \text{GeV}$$

- unphysical scenario with light singlet-like Higgs h_1

Conclusion & Outlook

Conclusion

- ongoing effort for precise predictions of Higgs-masses in NMSSM

Outlook

- finalizing full 1-loop contribution
- comparison of full 1-loop results with existing tools: NMSSMTools, NMSSMCALC
- implementation of dominant 2-loop contributions into FeynHiggs

Backup

NMSSM: Superpotential

$$\mathcal{W} = \; Y_t \widehat{Q}\widehat{H}_2\widehat{u} - Y_b \widehat{Q}\widehat{H}_1\widehat{d} - Y_\tau \widehat{L}\widehat{H}_1\widehat{l} + \lambda \widehat{S}\widehat{H}_2\widehat{H}_1 + \frac{\kappa}{3}\widehat{S}^3$$

$$\widehat{S} = v_s + S + \sqrt{2}\;\vartheta\widetilde{S} + F\text{-term}$$

$$\mathcal{L}_{\text{Soft}} = \left\{ -\frac{1}{3}\kappa A_\kappa S^3 - \lambda A_\lambda S H_2 H_1 + \text{h. c.} \right\} - m_s^2 \left|S\right|^2 + \ldots$$

$\Longrightarrow$ additional Higgs- and Neutralino-fields

Calculation: Mass-Matrices (CP-conserving)

- 3×3-mass matrices for electrically neutral scalars
  $\mathcal{M}^2_{\phi\phi\phi}$, $\mathcal{M}^2_{\chi\chi\chi}$
- 2×2-mass matrix for electrically charged scalars
  $\mathcal{M}^2_{\phi^-\phi^+}$

Set of independent parameters to represent mass-matrices:

$$\mathrm{e},\ M_Z^2,\ M_W^2;\ T_{\phi_1},\ T_{\phi_2},\ T_{\phi_s};\ \lambda,\ \kappa,\ A_\kappa;$$
$$M^2_{H^\pm},\ \tan\beta,\ \mu_{\mathrm{eff}}\,(=\lambda v_S)$$

Calculation: Renormalization Conditions

$$e,\ M_Z^2,\ M_W^2;\ T_{\phi_1},\ T_{\phi_2},\ T_{\phi_s};\ \lambda,\ \kappa,\ A_\kappa;\ M_{H^\pm}^2,\ \tan\beta,\ \mu_{\text{eff}}$$

- masses are renormalized on-shell
  $$M_Z^2\ ,\ M_W^2\ ,\ M_{H^\pm}^2$$
- electric charge renormalized in the Thompson-limit
- tadpole contributions at loop order should not alter classical minimum
  $$\delta T_{\phi_i} = -T_{\phi_i}$$
- rest of the parameters renormalized $\overline{\text{DR}}$

Calculation: Outline

Calculation of 1-loop contributions in three steps:

1. leading Yukawa approximation (LY): contribution of $t/\tilde{t}_{1,2}$ in gaugeless limit and vanishing external momenta
2. contribution of full quark-/squark-sector (N_c)
3. full contribution

Calculation: Outline

Calculation of 1-loop contributions in three steps:

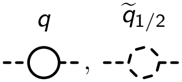
1. leading Yukawa approximation (LY): contribution of $t/\tilde{t}_{1,2}$ in gaugeless limit and vanishing external momenta
2. contribution of full quark-/squark-sector (N_c)
3. full contribution

Status of the three steps:

1. finished, result UV-finite
2. finished, result UV-finite
3. work in progress

Calculation: Leading Yukawa Approximation MSSM

- leading contribution from Yukawa-couplings



$$: \; Y_q^2 \propto \left(\frac{m_q}{M_W}\right)^2$$

- other contributions suppressed at least by factors

$$Y_t^{-1} \propto \frac{M_W}{m_t}, \; Y_t^{-2} \propto \left(\frac{M_W}{m_t}\right)^2$$

Calculation: Leading Yukawa Approximation NMSSM

- leading contributions involving top Yukawa-couplings

$$\Sigma_{\phi_i\phi_j}(0) \sim Y_t^2 \propto \frac{m_t^2}{M_W^2} \qquad i,j \in \{1,\ 2\}$$

$$\Sigma_{\phi_i\phi_s}(0) \sim \lambda Y_t,\ \kappa Y_t \qquad \lambda, \kappa < 1$$

$$\Sigma_{\phi_s\phi_s}(0) \sim \lambda^2,\ \kappa^2, \lambda\kappa \qquad \lambda^2, \kappa^2, \lambda\kappa \ll 1$$

Calculation: Leading Yukawa Approximation NMSSM

- leading contributions involving top Yukawa-couplings

$$
\begin{aligned}
\Sigma_{\phi_i\phi_j}(0) &\sim Y_t^2 \propto \frac{m_t^2}{M_W^2} && i,j \in \{1,\ 2\} \\
\Sigma_{\phi_i\phi_s}(0) &\sim \lambda Y_t,\ \kappa Y_t && \lambda, \kappa < 1 \\
\Sigma_{\phi_s\phi_s}(0) &\sim \lambda^2,\ \kappa^2, \lambda\kappa && \lambda^2, \kappa^2, \lambda\kappa \ll 1
\end{aligned}
$$

$\Longrightarrow$ reduces necessary set of renormalization constants

Calculation: Leading Yukawa Approximation NMSSM

- leading contributions involving top Yukawa-couplings

$$\Sigma_{\phi_i\phi_j}(0) \sim Y_t^2 \propto \frac{m_t^2}{M_W^2} \qquad i,j \in \{1,\ 2\}$$
$$\Sigma_{\phi_i\phi_s}(0) \sim \lambda Y_t,\ \kappa Y_t \qquad \lambda, \kappa < 1$$
$$\Sigma_{\phi_s\phi_s}(0) \sim \lambda^2,\ \kappa^2, \lambda\kappa \qquad \lambda^2, \kappa^2, \lambda\kappa \ll 1$$

$\Longrightarrow$ reduces necessary set of renormalization constants

- renormalized CP-even mass matrix in gaugeless limit

$$\hat{\mathcal{M}}^2_{\phi\phi\phi} = \begin{pmatrix} m^2_{\phi_1} + \hat{\Sigma}^{(\mathrm{MSSM})}_{\phi_1\phi_1}(0) & m^2_{\phi_1\phi_2} + \hat{\Sigma}^{(\mathrm{MSSM})}_{\phi_1\phi_2}(0) & m^2_{\phi_1\phi_s} \\ m^2_{\phi_2\phi_1} + \hat{\Sigma}^{(\mathrm{MSSM})}_{\phi_2\phi_1}(0) & m^2_{\phi_2} + \hat{\Sigma}^{(\mathrm{MSSM})}_{\phi_2\phi_2}(0) & m^2_{\phi_2\phi_s} \\ m^2_{\phi_s\phi_1} & m^2_{\phi_s\phi_2} & m^2_{\phi_s} \end{pmatrix} + \mathcal{O}\left(\frac{M_W}{m_t}\right)$$

Calculation: Quark-/Squark-Contributions NMSSM

- contributions of the full quark-/squark-doublet

  $\Longrightarrow$ all renormalization constants and all self-energies of the Higgs-sector are necessary

- outer momenta taken as non-vanishing

$$\hat{\Sigma}_{\phi_i\phi_i}\left(m^2_{\phi_i}\right),\ \hat{\Sigma}_{\phi_i\phi_j}\left(m^2_{\phi_i\phi_j}\right)$$

Backup: Renormalization Conditions, Details

- field renormalization

$$\delta Z_{\phi_i} = -\frac{\partial}{\partial p^2} \Sigma_{\phi_i \phi_i}\left(p^2\right)\Big|_{p^2 = M^2_{\phi_i}}^{\text{div.}}$$

- $\delta\kappa$, δA_κ fixed via fertex functions $\hat{\Gamma}_{\phi_1\phi_2\phi_s}$, $\hat{\Gamma}_{\phi_s\phi_s\phi_s}$
- $\delta\lambda$ obtained by

$$\frac{\delta\mu_{\text{eff}}}{\mu_{\text{eff}}}\Big|^{\text{div.}} = \left[\frac{\delta\lambda}{\lambda} + \frac{1}{2}\delta Z_{\phi_s}\right]^{\text{div.}}$$

Backup: Constraints on Parameters

- constraint from demanding stable minimum of potential [Ellwanger, Hugonie, Teixeira, '09]

$$A_\kappa^2 \gtrsim 9m_S^2$$
$$4\kappa v_S < -A_\kappa$$

- constraint from demand for no Landau-pole of Yukawa-couplings below the GUT-scale [Miller, Nevzorov, Zerwas '03]

$$\lambda^2 + \kappa^2 \lesssim 0.5$$

- suppression factors

$$Y_t \propto \frac{m_t}{M_W} \approx 2.16$$
$$Y_b \propto \frac{m_b}{M_W} \approx 0.05$$
$$\lambda^2,\ \kappa^2 \lesssim 0.7$$

Backup: References

FeynArts 3.7	hep-ph/0012260
FormCalc 7.4	hep-ph/9807565
LoopTools 2.7	hep-ph/9807565
NMSSMTools	hep-ph/0406215
NMSSMCALC	arXiv:1312.4788
[Ellwanger, Hugonie, Teixeira, '09]	arXiv:0910.1785
[Heinemeyer, Rzehak, Weiglein, et. al. '10]	arXiv:1007.0956
[Heinemeyer, Weiglein, Zeune, et. al. '12]	arXiv:1207.1096
[Miller, Nevzorov, Zerwas '03]	hep-ph/0304049